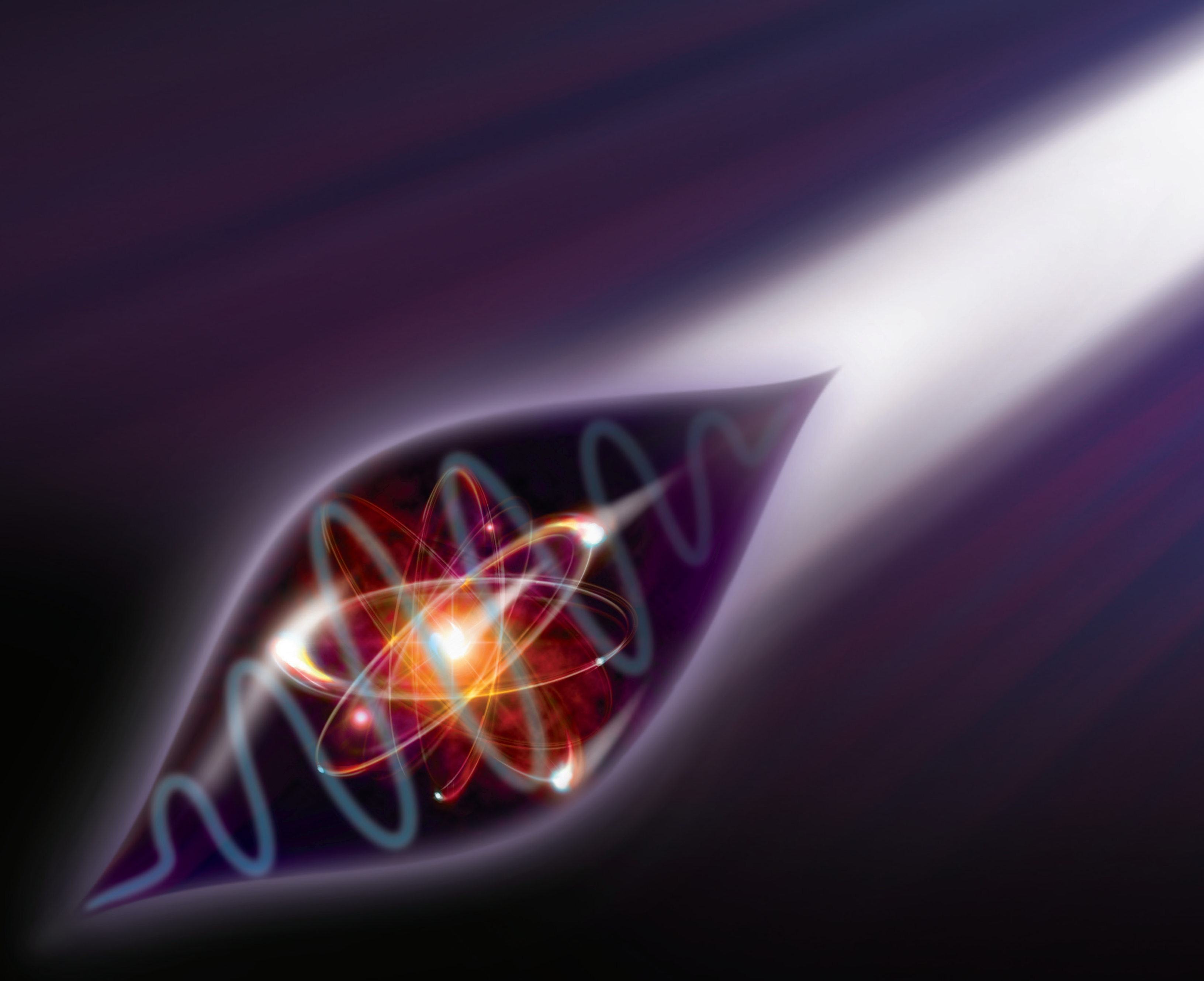
CIRCUITS OF ATOMS ON WIRES OF LIGHT

A NEW KIND OF CIRCUITRY—WITH ELECTRONS ON CONDUCTING WIRES REPLACED BY ATOMS ON PATHS OF LASER LIGHT—IS USHERING IN NEW TECHNOLOGIES BOTH KNOWN AND UNKNOWN.



WHAT ARE THE PRACTICAL APPLICATIONS of your research? For some scientific endeavors, such as controlling nuclear reactions, the answers are immediately evident. In other cases, the full potential of a scientific discovery may not be realized until much later, such as when scientists first studied quantum mechanics without knowing it would lead to the transistor, the basis for all electronic computing technology. But for some research, the practical applications come in both varieties, as is the case for a new "atomtronic" matter-wave circuitry scheme created by Los Alamos physicists Malcolm Boshier and Changhyun Ryu.

"Our matter-wave circuitry can be used for an ultrasensitive navigation system that doesn't rely on GPS, and people are deeply interested in that," Boshier says. "And I'm confident it can be used for an atom-scale lithography system that would assemble tiny devices by delivering atoms to very precise locations, like an 'atom laser pointer.' But this capability is so new, it's like developing the first electronic components and having only the faintest glimpse of what will eventually come from them."

What exactly is a matter-wave circuit? Matter waves are roughly what they sound like: waves borne of matter particles, e.g. atoms, just as electromagnetic waves comprise light. But while light waves can be manipulated with fiber-optic cables and other standard optical components, such as lenses and mirrors, and can be used to construct practical technologies like communications networks, an analogous type of control over matter waves has proven elusive. Until now, that is. And how Boshier and Ryu accomplished it is nothing short of ingenious.

Constructive interference

Every undergraduate physics student learns about the wave-particle duality: different forms of matter and energy have the properties of both waves and particles. Light waves, for example, can be separated into distinct particles called photons and detected one at a time. They have momentum and can push against matter objects (very gently at everyday light levels) just like particles. Similarly, matter particles such as protons and electrons exhibit behaviors specific to waves, such as diffraction and interference, as when water waves pass through narrow openings and cross paths, respectively.

What is actually waving in a matter wave isn't simple to describe, but it produces readily observable outcomes nonetheless. Send matter particles through two narrow slits, and their wave nature emerges: the particles are more likely to appear on the other side of the slits in locations where the waves spreading out from each slit are in phase (say, both waves near their peaks) than in locations where they are out of phase (one near its peak and the other near its trough). For some technologies, such as certain types of high-precision sensors that rely on such wave interactions, matter waves are inherently better than light waves.

In a Sagnac interferometer—the device Boshier cited as a GPS-free navigation instrument—waves sent both directions around a loop interfere at their collision point. The larger the loop, the greater the device's precision. And the degree to which the converging waves are in phase, as evident in the resulting interference pattern, provides information about how the spatial orientation of the loop has been changing. Because the wavelengths of matter waves (or light waves) are mathematically related to the momentum of matter particles

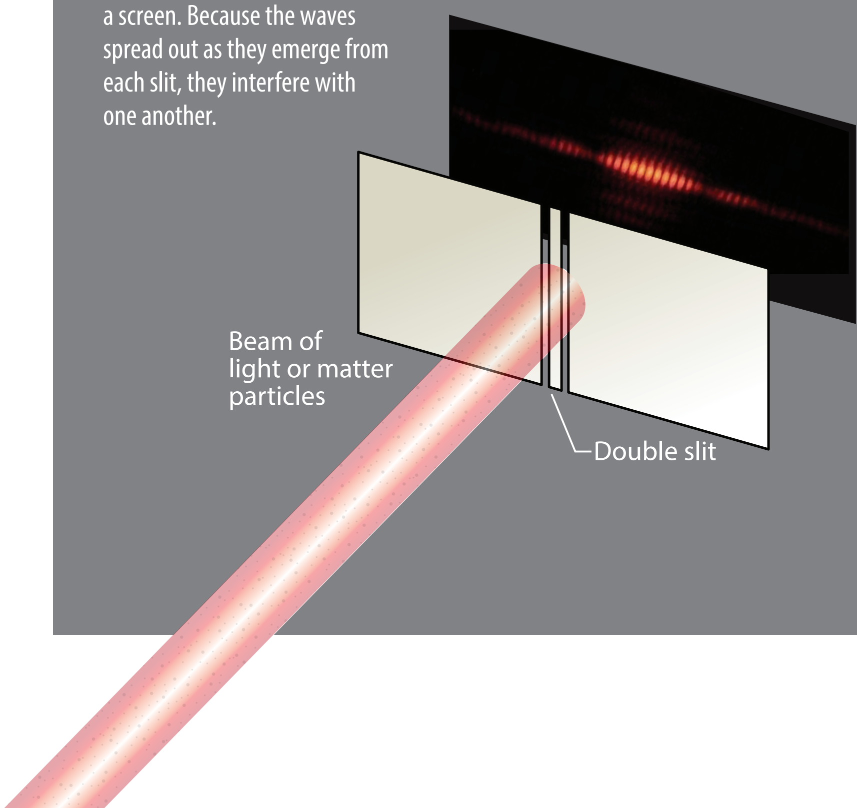
IT'S LIKE FIBER OPTICS, BUT WITH THE ROLES OF MATTER AND LIGHT REVERSED.

Wave-particle Duality

Matter and energy exhibit a wave-particle duality: particles act like waves and waves act like particles.

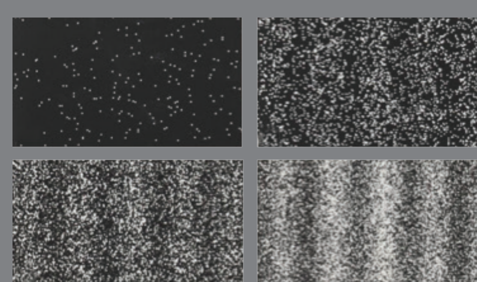
In a double-slit experiment, a beam of either light waves or matter particles passes through two slits and is then imaged on a screen. Because the waves spread out as they emerge from each slit, they interfere with one another.

With light waves, this interference produces a pattern of alternating light and dark patches on the screen.



CREDIT: Jordgette/Wikimedia Commons

With matter particles, such as electrons, the impact point for each particle striking the screen is recorded. Even if the particles are fired off one at a time, an interference pattern eventually accumulates, demonstrating the wave nature of particles. Successive frames show what happens as more particle impacts accumulate.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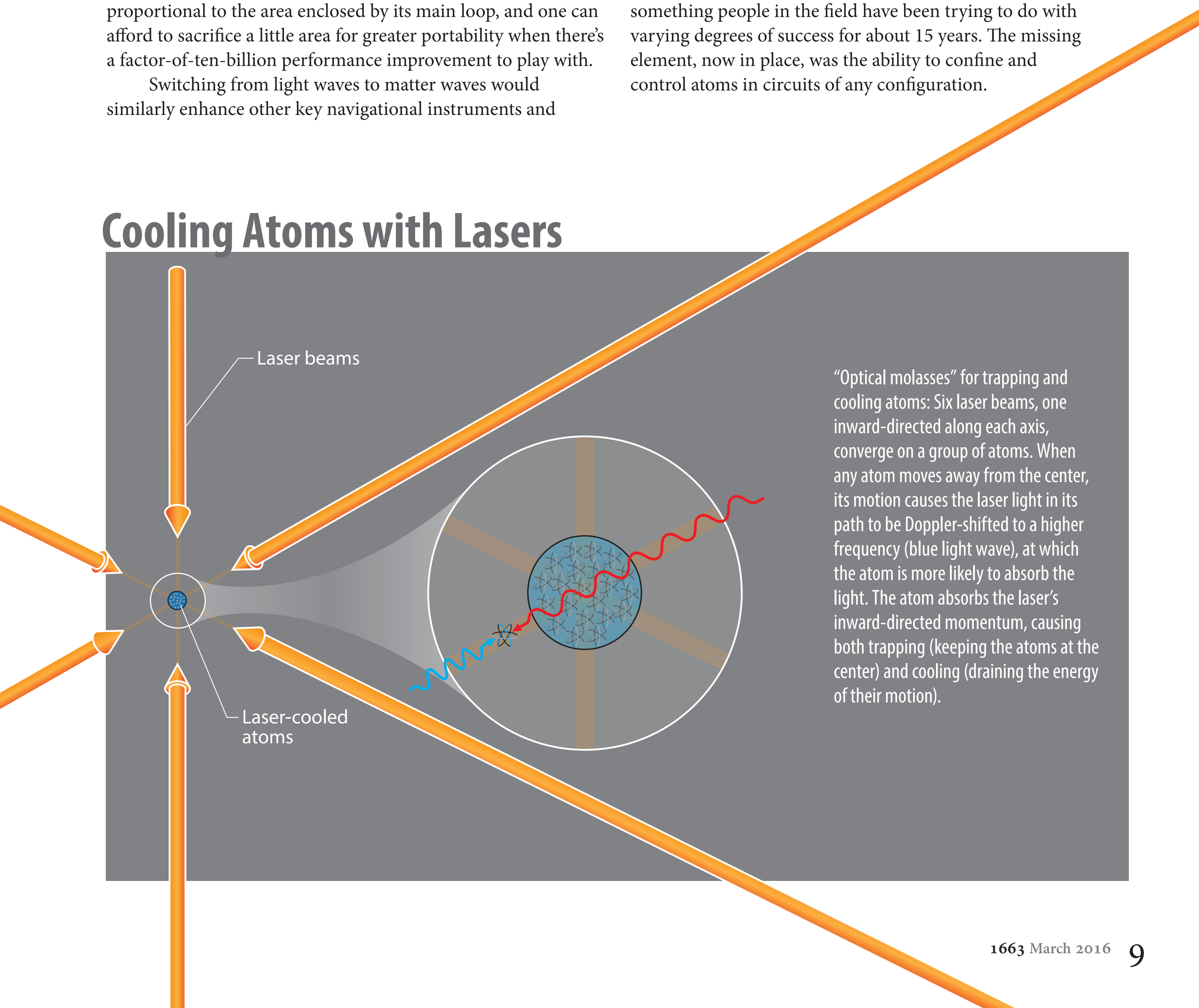
(or photons), the motion of the interferometer itself influences the interference pattern in a traceable way.

Already, Sagnac interferometers based on waves of laser light are used on submarines, essentially acting as high-end gyroscopes to keep track of how the vessel has turned and reoriented since the last time it surfaced for a GPS fix. Similarly, one can imagine special ops personnel tracking their motion through enemy bunkers, or spelunkers tracking their motion through underground caves, out of sight of any GPS satellites, with such an interferometer. There's just one problem: Sagnac interferometers accumulate measurement errors the longer they are used without calibrating off a GPS signal. Yet due to the physics involved, an equivalent Sagnac interferometer using atom-based matter waves instead of light waves would be about ten billion times more sensitive, in principle allowing errors to accumulate for much longer without significantly jeopardizing the accuracy of the readout. In addition, the atom-based version could be made much smaller than its light-based counterpart because a Sagnac interferometer's performance is proportional to the area enclosed by its main loop, and one can afford to sacrifice a little area for greater portability when there's a factor-of-ten-billion performance improvement to play with.

Switching from light waves to matter waves would similarly enhance other key navigational instruments and sensors. Interferometers that split a matter-wave beam in two can later compare the two beams for phase changes that belie wavelength changes and their corresponding momentum changes. For example, if one of the split-beam components is above the other and therefore moves through a slightly different gravitational field, then the resulting interference pattern can be used to infer subtle changes in gravitational-field strength. Such changes might be caused by changes in the underlying earth, such as when passing over a large deposit of heavy metals or a hollowed-out underground facility. And because there is no observable difference between constant acceleration-causing gravity and constant acceleration caused by anything else, the same type of matter-wave interferometer would work equally well as a high-sensitivity gravimeter or accelerometer. The latter could provide precise motion data to complement a Sagnac interferometer's detailed rotation data, for a more complete navigational instrumentation package.

Boshier and Ryu have completed successful proof-of-principle experiments for each of these applications—something people in the field have been trying to do with varying degrees of success for about 15 years. The missing element, now in place, was the ability to confine and control atoms in circuits of any configuration.

Cooling Atoms with Lasers



"Optical molasses" for trapping and cooling atoms: Six laser beams, one inward-directed along each axis, converge on a group of atoms. When any atom moves away from the center, its motion causes the laser light in its path to be Doppler-shifted to a higher frequency (blue light wave), at which the atom is more likely to absorb the light. The atom absorbs the laser's inward-directed momentum, causing both trapping (keeping the atoms at the center) and cooling (draining the energy of their motion).

Canvas of light

Creating useable matter waves relies on two main achievements: establishing a coherent collection of atoms, so that each atom contributes to the same interference pattern without canceling one another out, and steering them along a narrow path akin to a wire. Everyone in the research community seems to agree on how to accomplish the first objective, but the leading approach for the second objective has long been plagued with difficulty. The general idea was to construct nonphysical wires for the matter waves with carefully arranged magnetic fields. But because the magnetic fields would have to be almost perfectly smooth, the surfaces of the metal used to produce them would need to be comparably smooth. And so far it has proven impossible to create conductors with sufficiently smooth surfaces at the nanoscale.

CIRCUITRY MADE OF LIGHT CAN BE INSTANTLY RECONFIGURED TO SUIT ANY NEED ON THE FLY.

Boshier and Ryu decided to go another way entirely. Instead of magnetic fields, they chose to confine, align, and drive rubidium atoms with lasers, the electromagnetic waves of which include electric fields that oscillate back and forth. With each reversal, these electric fields rearrange the atoms' electrons to make them align with the electric field. If the field at a given instant is oriented in such a way as to push electrons in a particular direction, then each atom's electrons slide slightly that direction while still remaining bound to the atom.

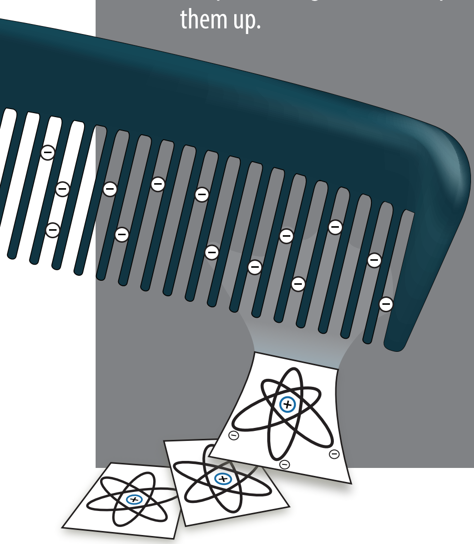
The same thing happens when a plastic comb is negatively charged after dragging electrons off of someone's hair, and then brought close to a shred of paper. The electrons in the paper are pushed away by the negative-negative repulsive force. Then, because the paper's positively charged atomic nuclei are, on average, slightly closer than its electrons to the negatively charged comb, the paper is attracted to the comb.

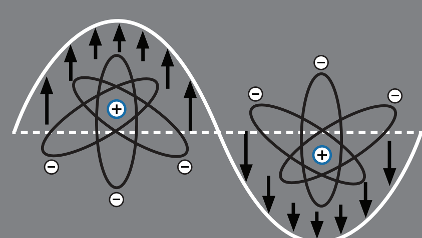
Similarly, Boshier's and Ryu's atoms are attracted to the highest-intensity part of the laser-induced electric field. Therefore the atoms won't drift away from the laser light. And each time the laser's electromagnetic wave reverses direction, the atoms' electrons shift in response, so the atoms continue to be drawn toward wherever the light is most intense. In this way, the lasers trap the atoms. Moreover, the same approach can be used to start the atoms moving along a circuit by creating a laser-intensity gradient to attract them toward the brightest region. Then, because the whole experiment takes place in a vacuum, the atoms maintain their motion even after the gradient is discontinued because there is no friction or air resistance to slow them down.

Controlling Atoms with Lasers

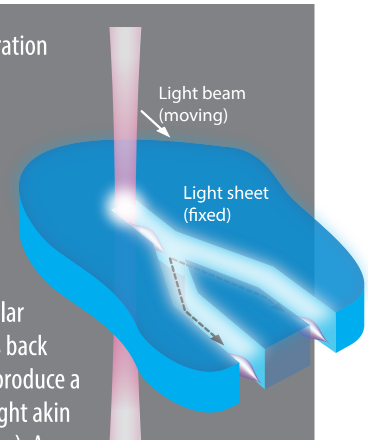
An electric field causes materials to polarize, slightly shifting their positive and negative charges into a configuration that attracts the materials toward the source of the electric field.

A comb strips electrons from hair, giving the comb an overall negative charge, which produces a corresponding electric field. Scraps of paper near the comb become polarized as a result (indicated by the stretched atom on the uppermost scrap), allowing the comb to pick them up.

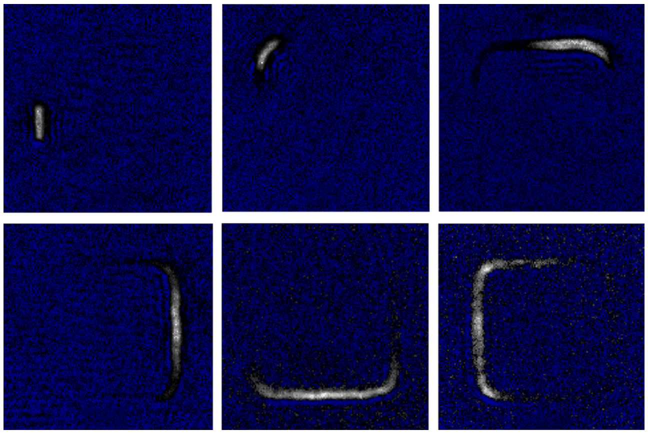


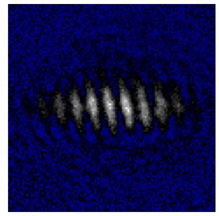


Electric fields intrinsic to laser-light waves have the same effect: nearby atoms become polarized and are therefore drawn into the laser beam and held there. As the laser-light wave oscillates, its electric field reverses direction, but that causes the atoms' polarization to reverse direction too, so the force of attraction between the atoms and the laser beam is unchanged.

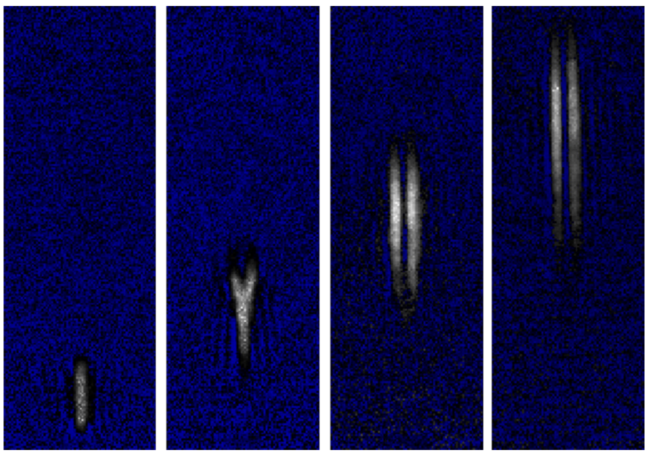


To guide matter waves, electric fields from a laser beam are used to trap atoms and channel them along a particular path. One laser scans back and forth rapidly to produce a horizontal sheet of light akin to a circuit board (blue). A second laser (pink) pierces through the light sheet perpendicularly and scans about rapidly as well, tracing out a circuit pathway on the horizontal light sheet. The second laser is focused so that its most concentrated, most intense part intersects the horizontal light sheet, so the atoms are tethered to the circuit path marked by the intersection of the two beams. The path can do anything; shown here, it forms a Y-junction, one of the forms successfully demonstrated by Los Alamos researchers.





Los Alamos researchers validated key aspects of matter-wave circuits, including bends (upper panels), splits (lower panels), and interference patterns from split beams (right).



Two perpendicular lasers sustain the matter-wave circuitry. The first sweeps from side to side, tracing out a sheet of light to act as the circuit board. The side-to-side motion is too rapid for the trapped atoms to "notice," forming the illusion of a smooth light sheet, in much the same way that individual frames in a 24-frame-per-second animation change too rapidly to notice, forming the illusion of smooth motion. The second laser is oriented vertically and adjusted so that its focus is narrowest (most intense) where it crosses the plane of light from the first laser. This second laser traces out a path, effectively painting a wire on the light-sheet circuit board.

"If we want our atom stream to turn, we paint a bend in the circuit with the vertical laser," Boshier explains. "Our lasers adjust much more quickly than the atoms move, so we can easily change the circuit at any time by painting different lines ahead of the atoms. The result is a lot like fiber optics, but with the roles reversed: it's light guiding matter instead of matter guiding light."

The atoms move along the painted circuits at about 20 millimeters per second. That's much faster than electrons typically "drift," in physics parlance, through a wire. But because the wire is chock full of conduction electrons, even a very slow overall drift can convey a large current of electricity.

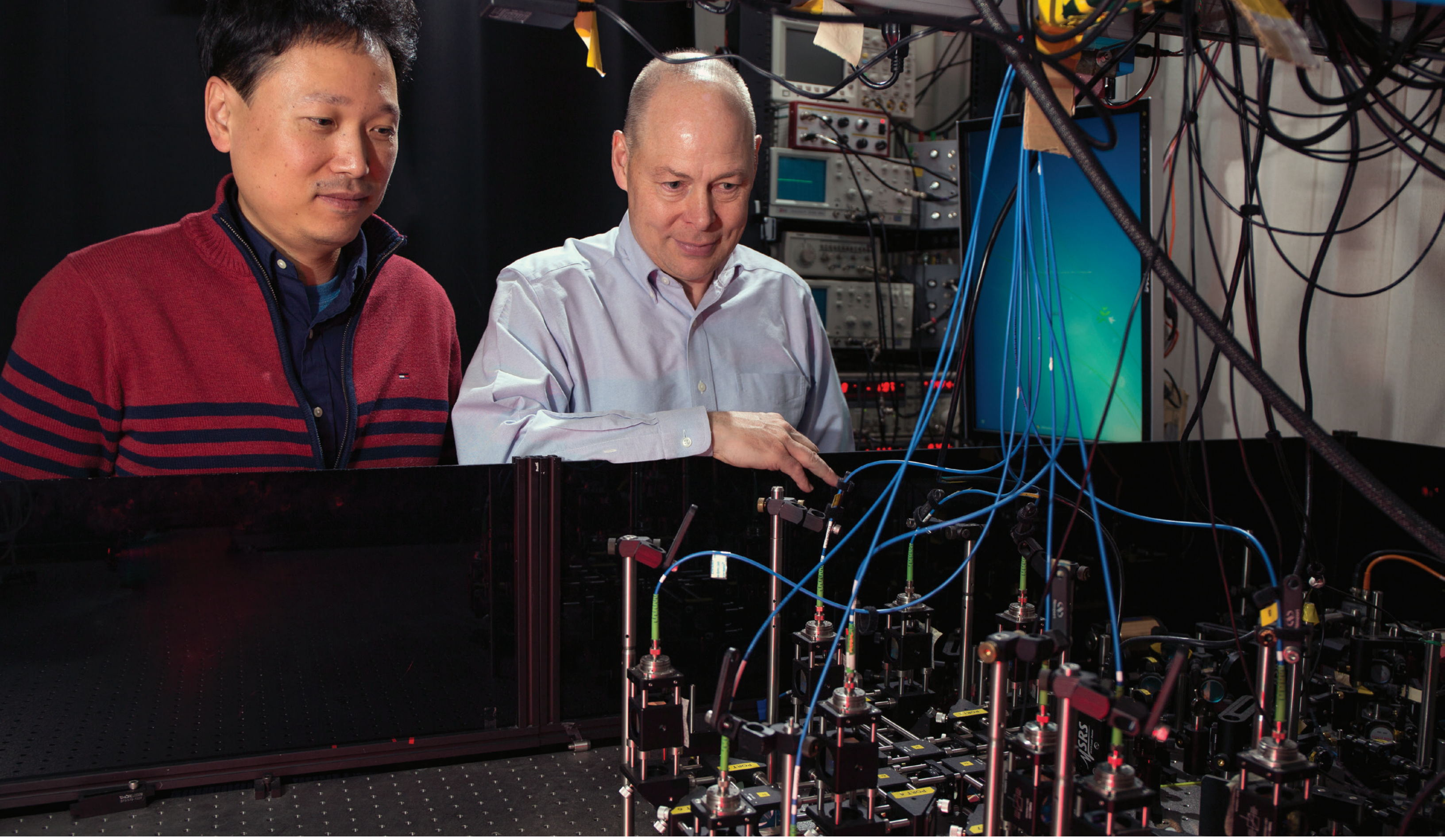
Boshier and Ryu accomplished something similar with matter waves, too—flooding an entire painted circuit with atoms. The result is a superfluid atom circuit, analogous to the superconducting electrical circuit often used in ultrasensitive magnetometers called SQUIDs (superconducting quantum interference devices). The superfluid matter-wave circuits recently proved successful in detecting rotation and might further help to probe new aspects of fundamental physics. But as with matter-wave circuitry in general, their full impact is difficult to predict so early in their existence.

Cold shoulders of giants

Making matter-wave circuits functional depends on getting all the atoms into their lowest-energy, or ground, state and keeping them there. Whether turning, splitting, or interfering, the atoms must remain in the ground state. Such a collection of atoms in the ground state is called a Bose-Einstein condensate (BEC), and maintaining a BEC requires not only very delicate control of the laser-painted circuitry, but also very, very cold atoms to start with.

FOR SOME APPLICATIONS, MATTER WAVES ARE INHERENTLY BETTER THAN LIGHT WAVES.

Just how does one cool a small collection of atoms? With more lasers, of course! In conjunction with a magnetic field to help keep the atoms in place, six laser beams are trained to converge on the atoms from each direction—left and right, ahead and behind, and above and below. The lasers are chosen at a frequency slightly lower than the peak frequency for the atoms to absorb the light. If a particular atom happens to be moving to the left, it will experience higher-frequency light waves coming from the left-side laser and lower-frequency light waves from the right-side laser due to the Doppler effect. (This is the same phenomenon that causes sound waves from a police siren to be higher pitched when the cop car is approaching and lower pitched when receding.) Therefore the leftward-moving

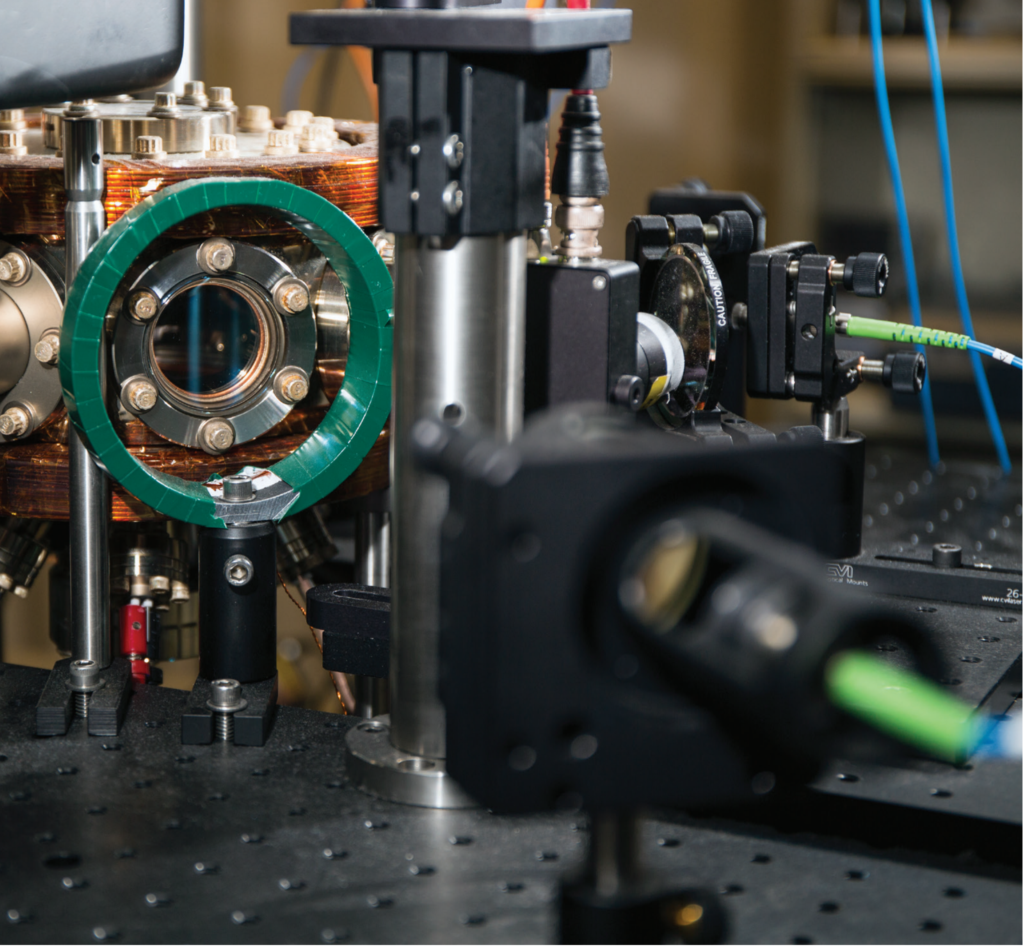


1 Changhyun Ryu (left) and Malcolm Boshier stand by their forest of lasers. Fiber-optic cables (blue) send the laser beams off to the duo's matter-wave circuit experiments.

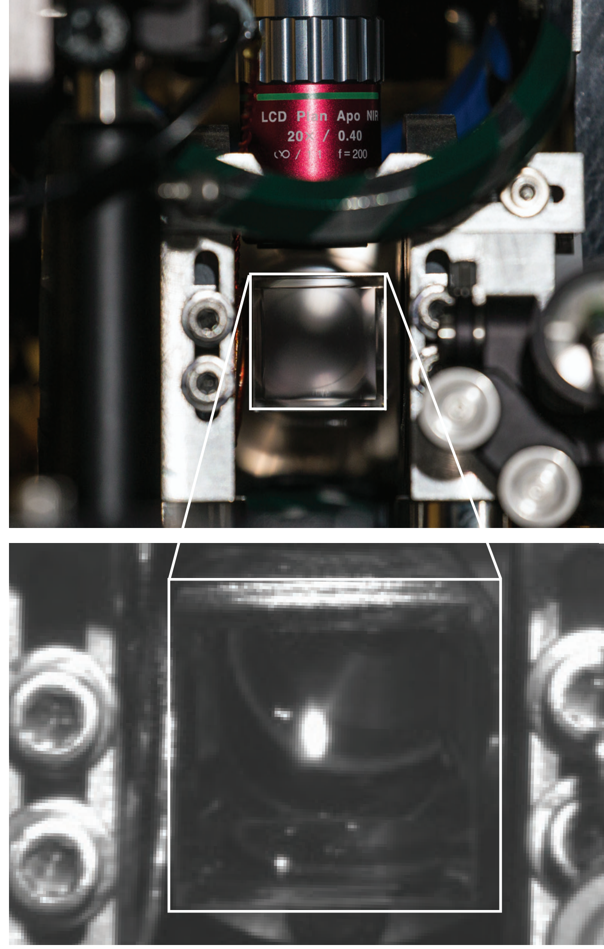
atom is more likely to absorb laser light from the left, the momentum of which pushes the atom to the right. The converse is also true: an atom moving to the right is more likely to be pushed to the left. Therefore these two lasers, together with the others pointing along the forward-backward and up-down axes, sap the atoms' motion—an effect sometimes referred to as "optical molasses." Whatever direction atoms are moving, the combination of lasers slows them down, making them sit relatively still at the center. And even though the atoms gain energy by absorbing laser light, they immediately re-radiate that energy away, so the lasers don't heat the atoms. On the contrary, the lasers produce a profound energy drain by slowing the atoms, cooling them to microkelvin temperatures—millionths of a degree above absolute zero—but still not quite cold enough.

To make coherent matter-wave circuitry, the atoms must be in an even colder BEC at 20 nanokelvins (billionths of a degree). The extra nudge colder happens similarly to the way humans cool by sweating: an evaporation process "boils off" the most energetic atoms from the sample (or the most energetic water molecules from the skin), reducing the average temperature of the ones left behind. After releasing the atoms onto the laser-light sheet upon which the matter-wave circuits are painted, Boshier and Ryu dial down the laser-trapping intensity to allow energetic atoms to evaporate away. The evaporation must be quite pronounced to achieve nanokelvin temperatures in the atoms that remain behind; all but the coldest few atoms out of every hundred thousand are allowed to leave.

Fortunately, while the laser-painted matter-wave circuitry application had to be largely invented from scratch, the technology for achieving a cold BEC didn't. In the past 20 years, trapping atoms with lasers and sustaining a BEC each resulted in a Nobel Prize, and each has become somewhat commoditized since. The former has evolved into an off-the-shelf device called a magneto-optical trap; it's a glass box a few inches across, with six laser entry points, sandwiched between electromagnets. The latter is also manufactured commercially, typically the size of small refrigerator but getting smaller,



2 The lasers (blue cables with green connectors) are directed through windows (inside green ring) into a magneto-optical trap. Four other lasers entering from other directions join the two visible here, converging to both trap and cool a collection of atoms called a Bose-Einstein condensate.



3 (Upper frame) The atoms are then shuttled to a glass box (beneath red cylinder) within a second magneto-optical trap. There, after further cooling, two more lasers create an optical circuit for the atoms to follow. One of these (not visible here) creates a horizontal sheet of light to act like a circuit board, while the other (red cylinder) paints the wires on it. (Lower frame) A monochrome infrared camera reveals a glowing bead of light coming from the trapped atoms as they absorb and re-emit laser light.

with tabletop systems and handheld components undergoing research and development. Even the painting lasers are the same mass-produced kind found in DVD players. It appears eminently possible that matter-wave technology could become both powerful and portable in the years to come.

Call of the wild frontier

Guided ultracold matter waves are the key to an emerging field—one promising enough to have the compelling name atomtronics but so new that most of its potential applications have yet to be demonstrated. Many researchers are interested in atomtronics, believing it will prove useful, maybe even transformative, in a variety of ways. One major application may turn out to be quantum computing. Another seems likely to be advanced signal processing. But whatever the application, it will rely on components analogous to those found in electronic and optical circuits, such as batteries, diodes, and transistors. Many such atomtronic-equivalent components have already been demonstrated by other researchers, and now Boshier and Ryu have added the critical missing link: a reliable, flexible method for joining these components together to make complex atomtronic circuits. They invented a system for launching BEC atoms into the laser-drawn wires and carefully adjusting the action of their lasers to guide matter waves around corners without damaging their ground-state coherence. They successfully created beam splitters and interferometers and used them in proof-of-principle demonstrations of advanced rotation and acceleration sensing systems.

And they have done it all with the ultimate in flexible circuitry: wires made of light that can be instantly reconfigured to suit any need on the fly. LDRD

—Craig Tyler